NASA CONTRACTOR REPORT

NASA CR-644

THERMAL MANIKIN

by Frank Gabron and John McCullough

Prepared by
ARTHUR D. LITTLE, INC.
Cambridge, Mass.
for Manned Spacecraft Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1966

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Acknowledgments

Arthur D. Little, Inc. wishes to acknowledge the efforts of Mr. James Waligora of the Crew Systems Division of the Manned Spacecraft Center who acted as Technical Monitor for the subject contract.

Also, credit is due Mr. Frank Trantanella of Wang Laboratories, Inc., Tewksbury, Massachusetts, who, under subcontract to Arthur D. Little, Inc., was responsible for the design and fabrication of the Temperature Logging-Power Control System.

Introduction

Man is capable of efficient operation only when the conditions of his body environment are kept within narrow limits. In the hostile environment of space, he must be provided with a space suit with built-in comfort-conditioning capabilities. Unless the space suit meets certain thermal requirements, man's basic physiological mechanisms will be impaired, and his work effectiveness reduced.

In order to test the value of various space suit designs and their attendant clothing assemblies and conditioning systems, simulated environmental and operational conditions are imposed. It is not desirable to expose the astronaut to tedium and/or hazards of the full developmental test sequence and, therefore, a thermal manikin which simulates the individual's homeothermy represents a useful tool.

This report deals with the fabrication and qualification tests of an anthropomorphic Thermal Manikin and Temperature Logging-Power Control System designed to simulate regional heat losses at relatively low skin temperatures where sweating is not present.

The manikin and associated data logging system were designed in accordance with the specifications outlined in NASA RFP No. MSC 64-1449P, Thermal Manikin, dated June 6, 1964.

This report is intended to summarize the description of the system. More detailed information on the operation of the system, including a description of methods used to don either Apollo or Gemini space suits is presented in Ref. 2.

I. THERMAL MANIKIN

The thermal manikin is divided into 17 thermally isolated regions in order to permit the simulation of heat loss variations which exist over different body regions. A list of the various regions and their surface areas are presented in Table 1.

Each region of the manikin is equipped with a platinum resistance thermometer and resistance heating elements which are used to simulate metabolic rates.

The dimensions of the manikin correspond to 50th percentile measurements in an eight size height-weight Air Force flying personnel sizing program. A photograph of the manikin is presented in Figure 1, and the mechanical assembly illustrating the articulation limits of the joints and separation planes is presented in Figure 2.

The thermal manikin is constructed of cast aluminum (1100 series) sections connected with either micarta joints or spacers. The use of micarta, which has a low thermal conductivity, permits the thermal isolation of the 17 regions. The cast aluminum sections have a minimum wall thickness of approximately 3/16 inch. Flexible heating elements and resistance thermometers are affixed to the interior of each section. The locations of the heating elements and temperature sensors are shown in Figure 3. As shown in Figure 3, more than one heating element per region is used in order to minimize the temperature gradients that would exist if only a small portion of the region were heated.

The limb sections of the manikin are connected through specially constructed joints which provide the limited motion while insuring

Table 1

Manikin Regions and Areas

	Approximate Surface Area (ft^2)
Head	2.15
Chest	1.83
Abdomen	1.29
Back	2.47
Buttocks	1.94
Thighs	3.55
Calves	2.15
Feet	1.29
Arms	1.08
Forearms	0.86
Hands	0.75
Total	19.36

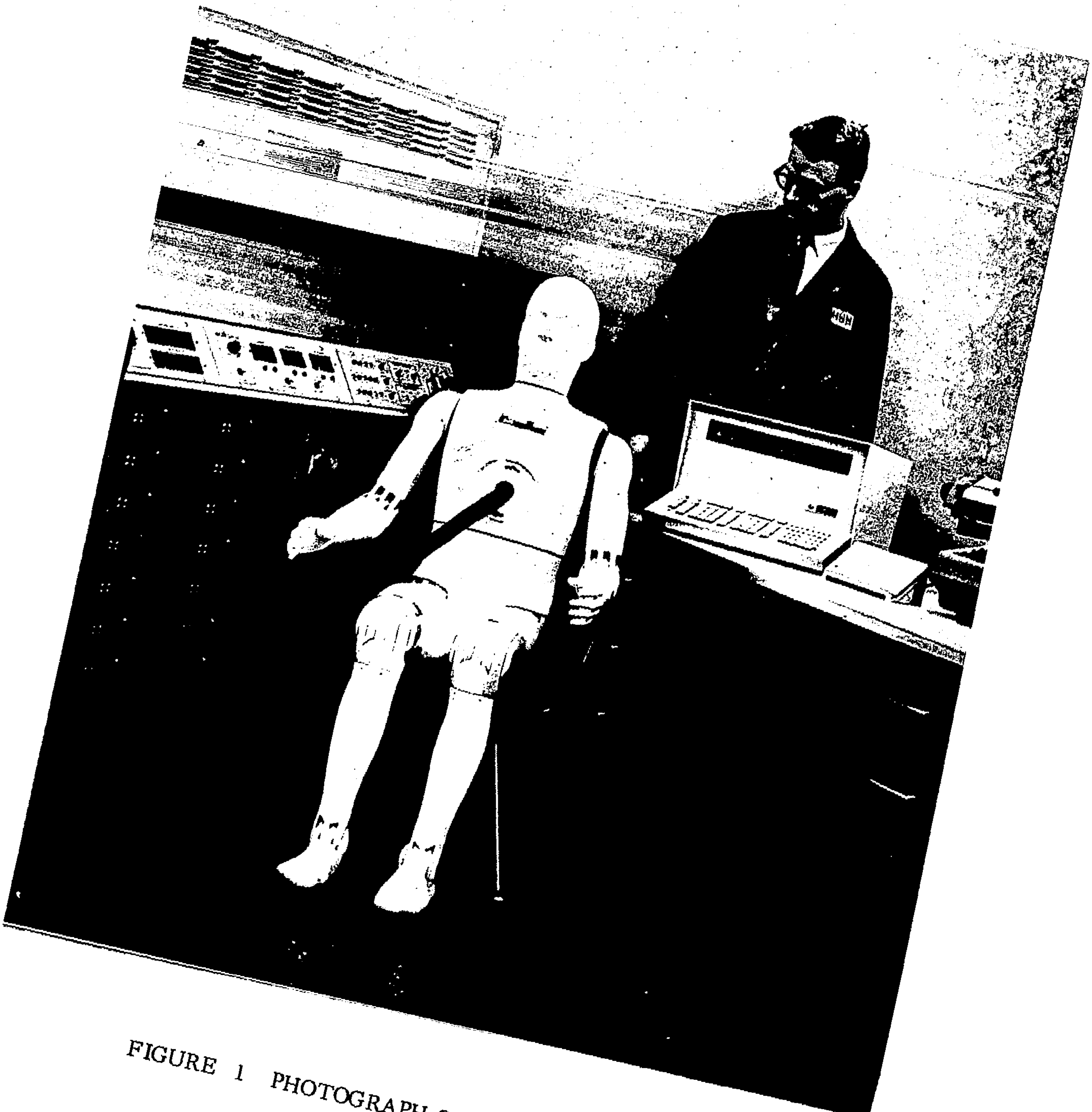

FIGURE 1 PHOTOGRAPH OF THERMAL MANIKIN

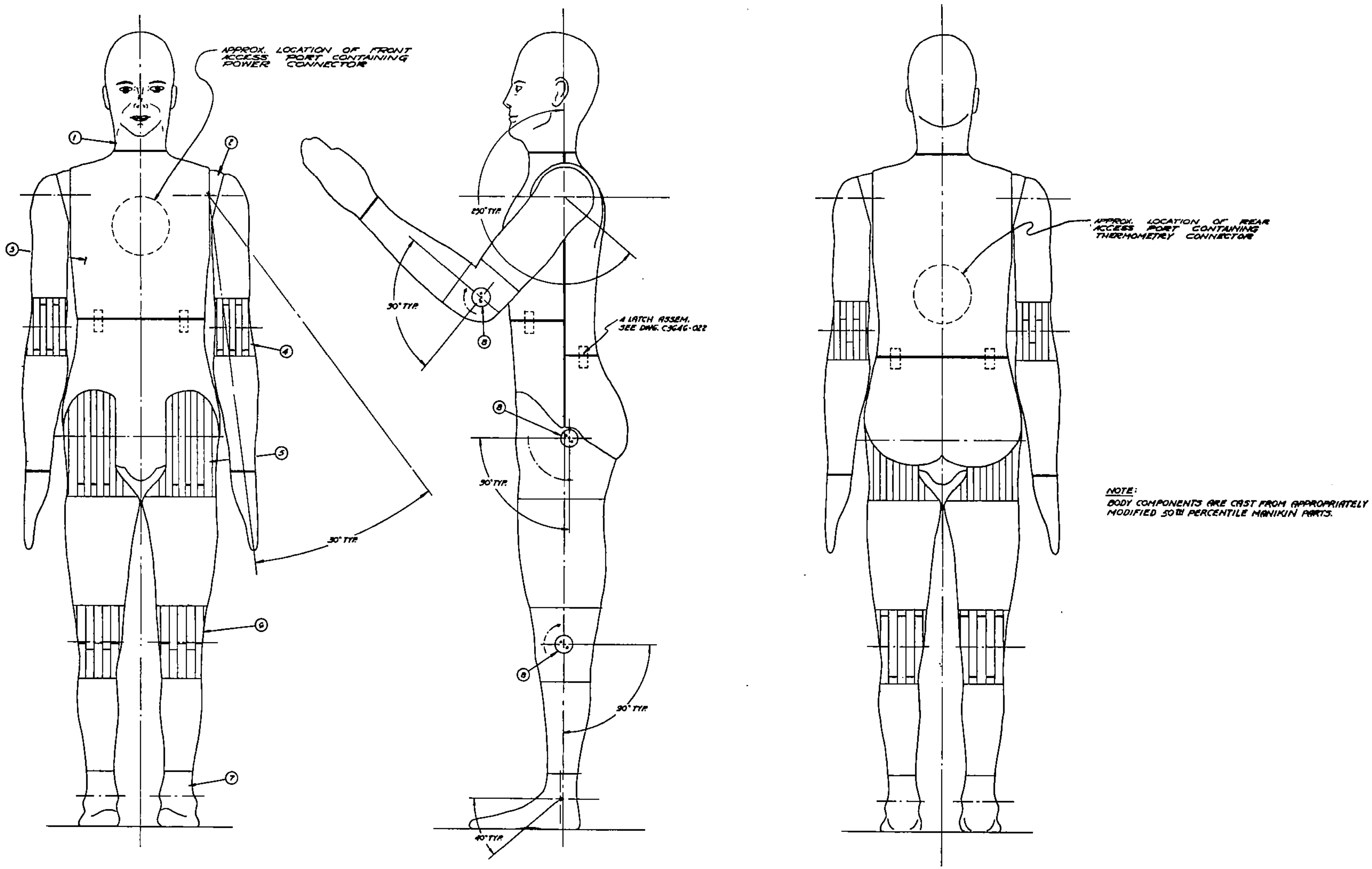

FIGURE 2 MECHANICAL ASSEMBLY

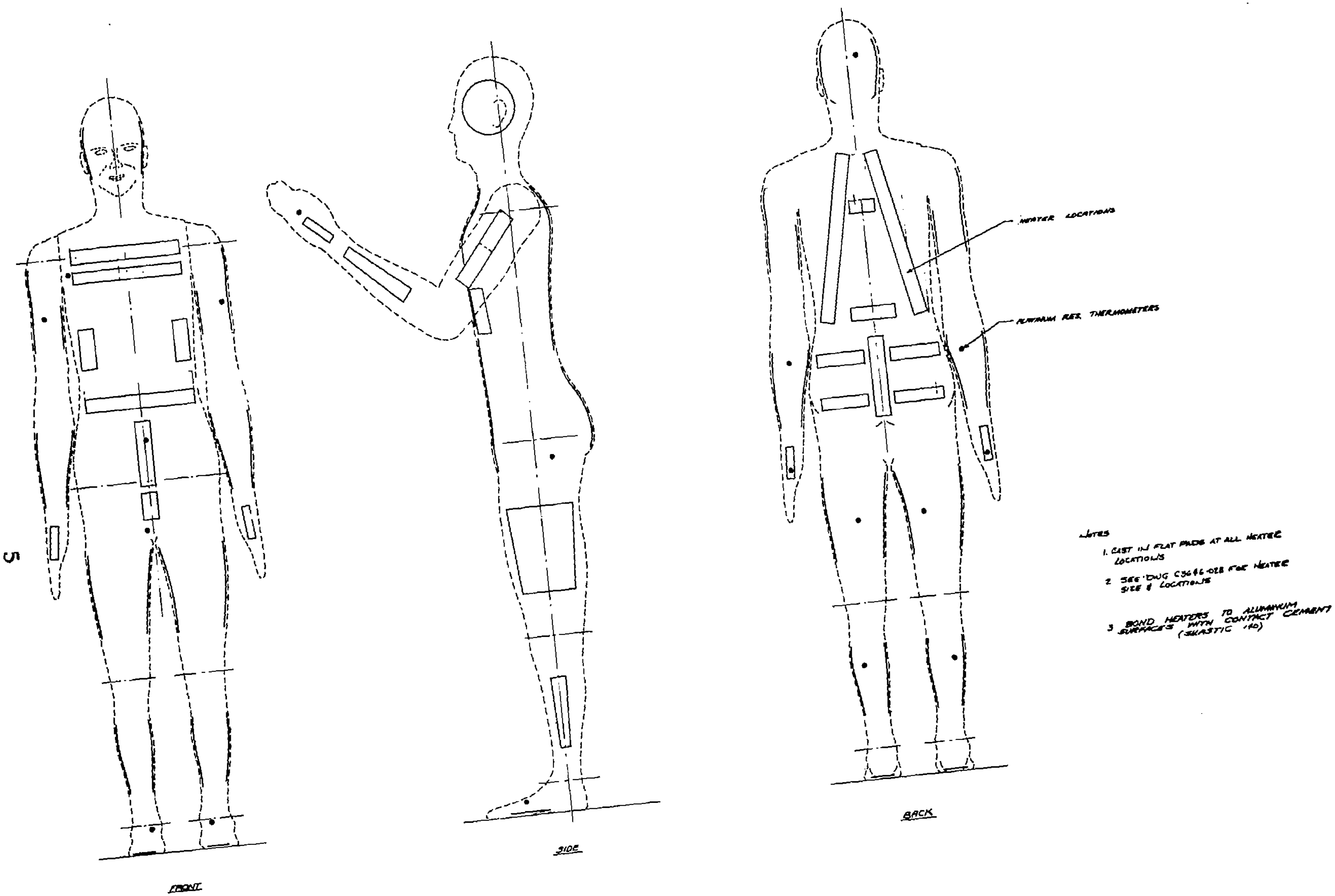

FIGURE 3 HEATER LOCATIONS

thermal isolation of the adjacent limb sections. These joints are constructed of alternate plates of aluminum and micarta in an inter-leaved design. This design simulates the shape of human joints, prohibits pinching of garments during donning, and lends itself readily to a locking system.

Joints are provided in the ankle, knee, hip, shoulder, and elbow regions to permit rapid disassembly and articulation so that the manikin can be easily donned in a pressure suit. To facilitate donning the manikin in a pressure suit or other test garment, the manikin is separable at the neck, shoulders and waist and is equipped with removable thumbs.

A photograph of the manikin clothed in a space suit with one arm locked in an upright position is shown in Figure 4.

The hip, knee and elbow joints may be locked in any position by use of spring loaded, pneumatic axle assemblies. The joints are unlocked by pressurizing the locking axle release bellows through an internal pressurization system. When the manikin is completely assembled, pressurization is accomplished by connecting a valve located under the removable thumb of each hand with a shop air line.

The head is equipped with a short, tapered, plug-socket combination joint equipped with retaining fingers spaced 180° apart which hold the joint together after it is assembled and rotated slightly in either direction. Access ports on the front and back of the torso are equipped with this same "twist-to-lock" feature. The ports provide access to the shoulder and waist joints.

The shoulder joints consist of ball and socket friction members which are squeezed together by the shoulder locking axle. The arms are

FIGURE 4 THERMAL MANIKIN DONNED IN SPACE SUIT

removed by unscrewing the retaining bolt located inside the torso and extracting the bolt and associated flange through the torso access port.

The thumbs are removable to facilitate inserting the arm into garments equipped with small diameter wrist ring connections. They are held in place by small permanent magnets embedded in the hand.

The waist joint is made up of four short tapered studs which are used for alignment and four associated "Camloc" latches. The torso assembly can be removed by reaching through the nearest torso port and releasing the four latches.

To provide for a high surface emittance, which is representative of the emittance of human tissue, the manikin is painted with a white epoxy paint (Cat-A-Lac Gloss White) which has an infrared emittance of approximately 0.87.

II. TEMPERATURE LOGGING-POWER CONTROL SYSTEM

A. Specifications

The Temperature Logging-Power Control System has the following functions:

1. Measuring and digitally recording the 17 regional temperatures (with an accuracy of approximately $\pm$ 0.5F) and an area weighted average temperature. Three spare channels are provided.
2. Measuring and digitally recording the power delivered to each region (with an accuracy of approximately $\pm$ 0.5 watts) and the total power.
3. Measuring and digitally recording the time in hours, minutes and seconds.
4. Controlling the power delivered to each region, as a linear function of temperature, with the slope and zero power intercept temperature individually adjustable, or, supplying a constant amount of power to each region independent of the temperature. The maximum input power is approximately 880 watts.

The results of qualification tests performed on the thermal manikin are presented in Appendix A.

B. General Description

The Temperature Logging-Power Control System comprises three basic elements, a system electronics console, a LOCI[1] digital computer, and

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1. Product of Wang Laboratories, Inc., Tewksbury, Massachusetts.

an IBM Model B typewriter. The LOCI digital computer is used to control the entire system through an input and output multiplexer. The electronics console houses the programmable DC power supplies for the manikin heaters, the signal conditioning equipment for the platinum resistance thermometers, digital data storage in three punched card readers, a digital clock, analog to digital converter, multiplexers and associated circuitry.

Photographs of the system illustrating the various components are presented in Figures 5 and 6, and a flow diagram of the electronics system is presented in Figure 7.

Because of the flexibility of the LOCI digital computer which is used to control the operation of the system, many different control functions can be accomplished by punching different cards for the LOCI program reader. However, the system is basically designed to regulate the power inputs to the manikin as a function of the measured skin temperature or to supply a fixed amount of power to each region and measure the resulting temperature. Two separate punched card programs are supplied to operate the system in either an "Automatic Power Control" mode or a "Fixed Power" mode. These and other programs which are primarily used for automatically checking the accuracy of the temperature logging and power control circuits are described in the "Operation and Instruction Manual" furnished with the system (Ref. 2).

In addition, the LOCI computer can be used separately from the manikin system. Operated as an extended desk-top calculator in the manual mode, the LOCI is capable of performing addition, subtraction, multiplication, division, exponentiation as well as taking logarithms and

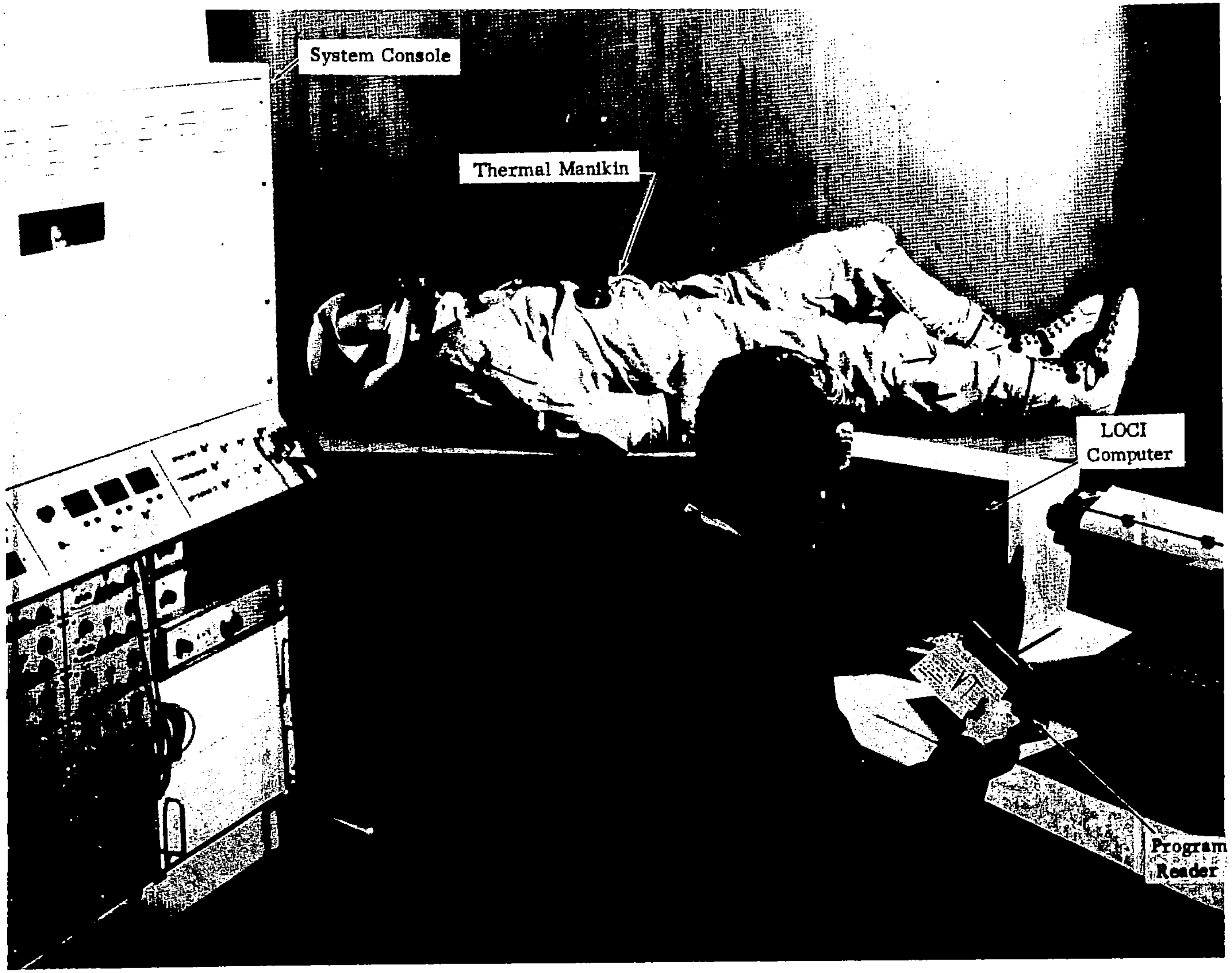

FIGURE 5 THERMAL MANIKIN & CONTROL ASSEMBLY

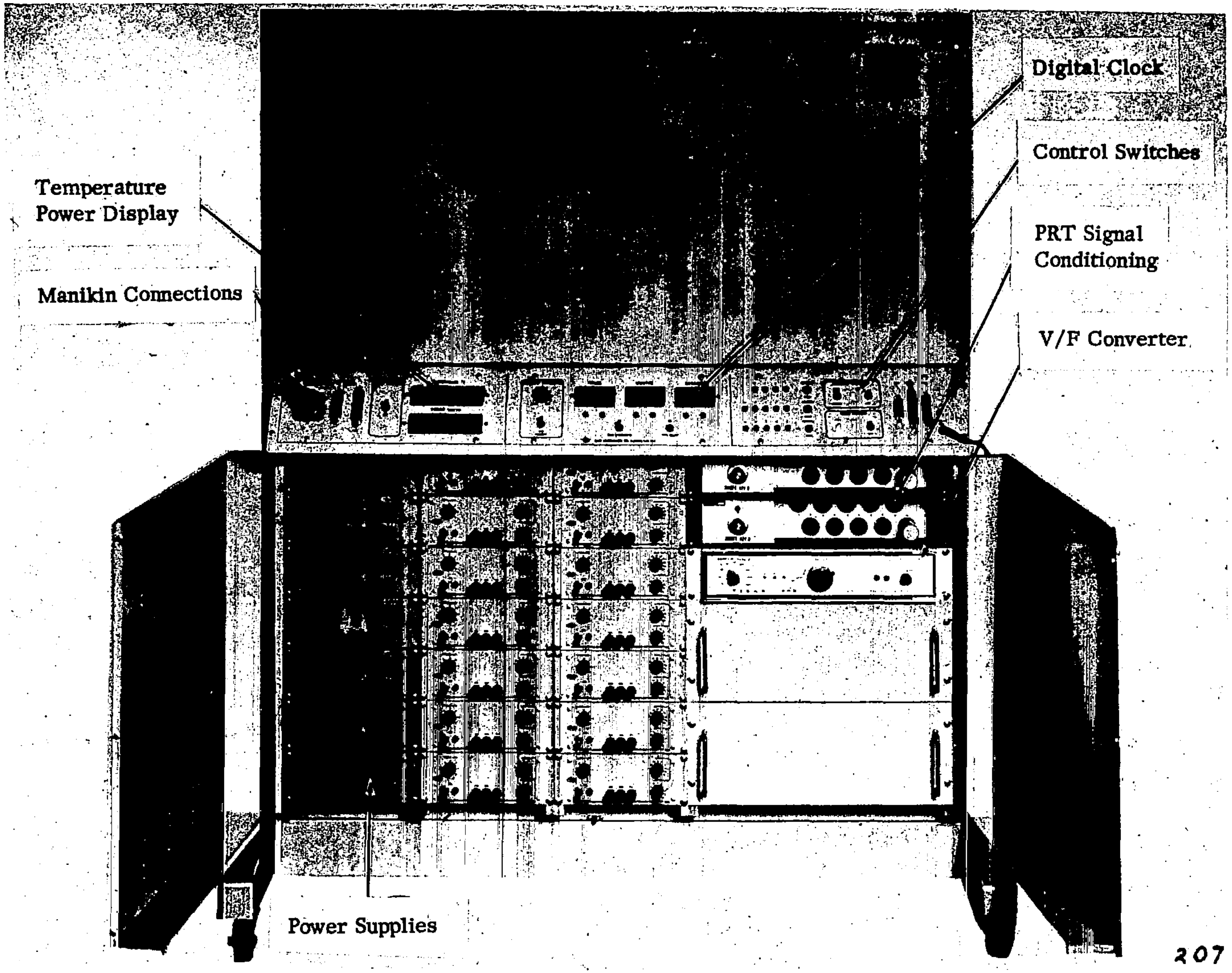

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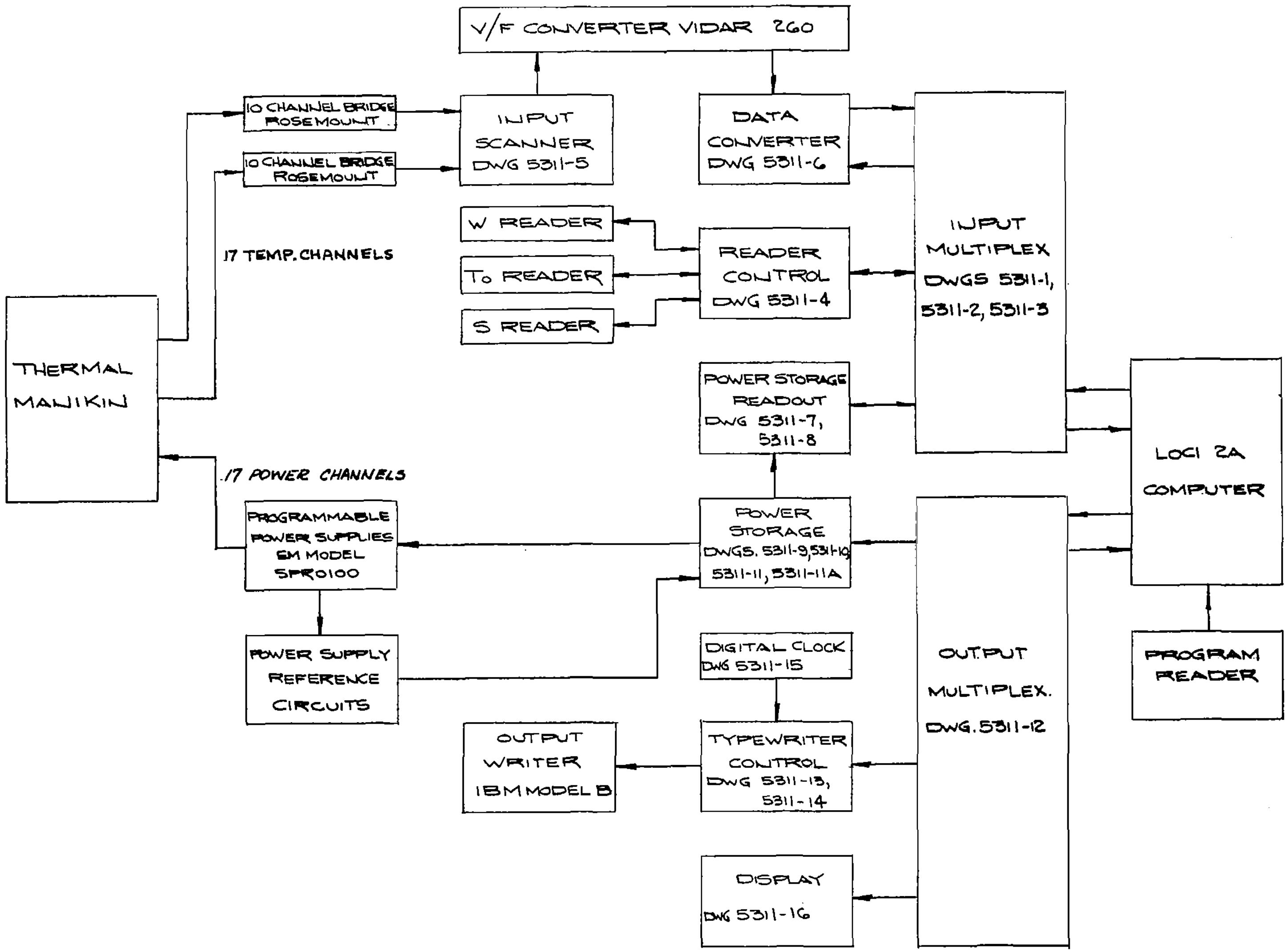
FIGURE 6 SYSTEM CONSOLE



* DRAWING NOS PERTAIN TO WANG LABORATORY DRAWINGS

FIGURE 7 SIGNAL FLOW DIAGRAM

extracting roots. For programmed operation as a computer, the LOCI has a flexible set of commands which can be used to program iterative procedures by use of the program card reader. A complete description of the operation of the LOCI computer and a number of programs are included in the Operation and Instruction Manual (Ref. 2).

In order to illustrate the characteristics of the Temperature Logging-Power Control System, we have outlined below the operation of the system in the "Automatic Power Control" mode. In this mode, the power delivered to each of 17 regions of the manikin is controlled in accordance with the equation

$$P = S\ (T_o - T) \tag{1}$$

where:

T - measured temperature (F)
S - slope (watts/F)
T_o - intercept temperature (F)
P - delivered power (watts)

Input data for the LOCI computer consist of S and T_o which are stored on cards, a program reader containing the necessary instructions to run the system and a card reader which is used to store area weighting factors required to compute the area weighted average temperature.

The numerical values of T_o, S, and the area weighting factors used on the cards are presented in Table 2. They can, of course, be changed by re-punching new cards.

Table 2

Values of Power Control Slope, Intercept Temperature and Weighting Factors

	S (watts/F)	W	T_o (F)
Head	0.765	0.111	100.4
Chest	2.440	0.095	98.2
Abdomen	1.380	0.067	98.1
Back	1.830	0.127	102.2
Buttocks	1.290	0.100	101.8
Thighs	0.810	0.092	100.0
Calves	0.590	0.056	101.8
Feet	0.390	0.033	98.4
Arms	0.570	0.028	100.6
Forearms	0.380	0.022	100.6
Hands	0.540	0.019	100.6

Note: Data from NASA RFP No. MSC 64-144P, Thermal Manikin.

The real time as measured by a digital clock is printed out by the typewriter. The temperature of a given region is obtained through the input scanner in analog form by use of a platinum resistance thermometer[1] and signal conditioning bridge system. The analog voltage is converted to a digital output by use of a voltage-to-frequency converter and counter.

The LOCI computer uses the measured temperature and equation (1) (values of T_o and S stored on cards) to compute the proper amount of power that should be delivered to the region. Through the output multiplexer, the power storage register of the programmable power supply is set at the proper value. The temperature and power for the region are displayed on the system console and are printed (in degrees F and watts) on the IBM typewriter. The power delivered and the temperature multiplied by the appropriate weighting factor are stored by the computer. The input multiplexer advances to the next channel and the entire process is repeated until all 17 channels have been scanned and printed. The accumulated area weighted average temperature and the total power are then printed.

The system cycles continuously sampling each of the 17 temperatures and resetting the power supplies. The data can be printed for each scan or at pre-selected time intervals by use of a console control switch.

C. Temperature Measurement

Temperature measurements are made on each of the 17 regions by use of platinum resistance surface temperature sensors. The maximum

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1. Rosemount Engineering Company, Minneapolis 24, Minnesota.

temperature range is 0.0°F to 99.9°F.

Each temperature sensor is part of a bridge circuit, which converts temperature values into a proportional millivolt output. The bridge circuits are calibrated with the sensors, so that all channels have identical outputs. The voltage range for each channel is 0 to 50 millivolts corresponding to a 0 to 100°F temperature span. The effects of sensor lead wire resistance are minimized by a special 4-wire connection to the bridge.

In addition to measuring individual temperatures of the 17 segments, an area-weighted average temperature is measured and recorded. The average is formed by summing the 17 temperatures, each multiplied by a constant weighting factor.

D. Power Control

The system is capable of operating in either of two modes: an automatic mode, where the power to each of the heater elements is controlled as a linear function of the temperature of that region, and a manual mode, where the power to each of the heater elements is set at some prescribed value.

In the manual mode, the maximum power delivered to any single region is 147 watts, and the total power is about 880 watts.

In the automatic control mode, the heater power to each region will be automatically varied in response to the temperature of the region, as measured by the resistance thermometer. The power will be a linear function of temperature, as defined by equation (1).

The actual power control function is accomplished by regulating a DC voltage which is applied to each heater element. The DC voltages are derived from highly regulated, remotely programmed power supplies, one for each heater. In order to use a voltage source for supplying the correct amount of power to each heater element, the heater elements were made to have a low temperature coefficient of resistance. The resistance of each heating circuit was accurately determined after installation by use of a precision resistance bridge. These values are used in setting the maximum output voltages of the power supplies.

As shown in Figure 7, the programmable power supplies are controlled through the output multiplexer by the LOCI computer. The power supplies are programmed by the computer on a percent of full scale basis. The actual full scale value for each supply is adjusted to compensate for resistance variations from heater to heater. Specifically, the computer uses the equation

$$G = \%\ F.S. = 100\,\frac{V}{V_{max}} = \frac{100\sqrt{P\,R}}{V_{max}} \qquad (2)$$

where:

G = percentage of power supply full-scale voltage
V = output voltage
V_{max} = maximum output voltage of each supply (adjustable)
P = power delivered to heater circuit
R = heater circuit resistance

Equation (2) can be reduced to

$$G = K\sqrt{P} \qquad (3)$$

where:

K = arbitrary constant

Note that by adjusting V_{max} for each power supply the numerical value of K can be made equal for all channels.

Thus, the LOCI computes the amount of power P to be delivered from equation (1) and uses a stored value of K to compute the percentage of full-scale voltage G that must be programmed into the power supply.

E. Time Measurements

The system contains an integral digital clock with a 100 Kc crystal-controlled oscillator as a time base. The time in hours, minutes, and seconds is displayed at the system control panel and is automatically printed at the beginning of each recording cycle.

F. Recording

The quantities to be recorded are 21 temperature measurements (17 segments of the manikin, plus one weighted average temperature, plus three spare channels), 18 power measurements (the power supplied to each of the 17 individual heaters, plus one measurement of total power), and time of the recording cycle.

The time required for one recording cycle as described above is approximately 40 seconds. The time required for one cycle when print-out is inhibited is approximately 20 seconds.

All data (time, temperatures and powers) are printed on paper by an IBM Model B output writer.

REFERENCES

1. Clifford, J. M., Requirements for the Thermal Control of a Manikin for Clothing Investigation, Industrial Medicine and Surgery, January 1963.

2. Operation and Instruction Manual - Thermal Manikin, Report to NASA MSC by Arthur D. Little, Inc., Contract NAS 9-3554, October 20, 1965.

APPENDIX A

TEST REPORT

PERFORMANCE OF THERMAL MANIKIN

TEST RESULTS

Test #1 Accuracy of Temperature Measurements

The manikin was mated with the temperature logging and control system and temperatures as measured by the 17 manikin platinum resistance thermometers were compared with temperatures measured by use of a calibrated copper-constantan thermocouple.

The thermocouple was calibrated in a water bath with a platinum resistance thermometer in the Instrumentation Standards Laboratory. The absolute error of the thermocouple temperature measurement is judged to be less than 0.1 F.

The results of two tests are presented in Table 1A. In Test 1, the manikin temperatures were measured at equilibrium without internal power at an ambient air temperature of approximately 75 F. In Test 2, power was applied to the zones of the manikin to elevate the zone temperatures above the ambient air temperature which was approximately 72 F. In Test 2, some errors were introduced in the thermocouple measurements due to heat losses from the leads.

TABLE 1A

TEMPERATURE CALIBRATION

	Test 1			Test 2		
	System F	TC F	Error F	System F	TC F	Error F
00	75.0	75.07	-0.07	80.3	80.17	+0.13
01	74.2	74.41	-0.21	82.8	82.75	+0.05
02	74.5	74.68	-0.18	80.9	80.47	+0.43
03	74.0	74.10	-0.10	81.7	81.79	-0.09
04	74.0	74.10	-0.10	80.4	80.38	+0.02
05	74.7	74.73	-0.03	78.4	78.17	+0.23
06	74.8	74.73	+0.07	78.3	78.13	+0.17
07	75.2	75.07	+0.13	78.7	78.33	+0.37
08	75.0	75.16	-0.16	78.4	78.33	+0.07
09	74.8	74.53	+0.27	78.5	78.15	+0.35
10	74.9	74.93	-0.03	78.2	77.97	+0.23
11	74.7	74.80	-0.10	79.9	79.68	+0.22
12	74.5	74.68	-0.18	80.2	80.08	+0.12
13	75.2	75.29	-0.09	78.3	78.13	+0.17
14	75.2	75.09	+0.11	78.9	78.67	+0.28
15	75.7	75.87	-0.17	78.1	78.15	-0.05
16	75.3	75.34	-0.04	78.7	78.51	+0.19

Test #2 Accuracy of Power Measurements

Each of the 17 manikin regions is heated by use of programmable power supplies. As a check on the power being delivered to each zone the power delivered as recorded by the data logging system operating in the automatic mode was compared with the power computed by voltage and resistance measurements.

The voltage being delivered by each d.c. power supply was measured at the console by use of a Cubic Co. digital voltmeter. The resistances of each heater circuit with and without lead wires were measured by a resistance bridge. The actual power delivered to the heaters was calculated from the expression

$$P_h = \frac{V^2}{R_T{}^2} R_h$$

where P_h - power delivered at heater

V - voltage drop across circuit

R_T - total resistance (leads plus heater)

R_h - heater resistance

The results are shown in Table 2A. The errors are seen to be less than 0.1 watt on the average. The maximum error is 0.16 watts. It should be noted, however, that the power is recorded only to the nearest tenth of a watt.

Test #3 Measurement of Time Response

To measure the time required for each region to reach an equilibrium temperature the manikin was allowed to equilabrate at room temperature

TABLE 2A

ACCURACY OF POWER MEASUREMENTS

(all values in watts)

Channel	Power Recorded	Power Measured	Error
00	7.0	7.04	-0.04
01	10.4	10.56	-0.16
02	7.3	7.29	+0.01
03	11.8	11.88	-0.08
04	10.7	10.78	-0.08
05	9.6	9.68	-0.08
06	9.3	9.39	-0.09
07	6.3	6.28	+0.02
08	6.3	6.33	-0.03
09	3.3	3.37	-0.07
10	3.4	3.43	-0.03
11	5.0	5.11	-0.11
12	5.2	5.29	-0.09
13	4.2	4.32	-0.12
14	4.3	4.41	-0.11
15	3.0	3.05	-0.05
16	3.1	3.19	-0.09

without power to any zone. The system was then turned on in the "automatic mode" (programmed skin temperature vs. power) until each region reached equilibrium. The temperatures were recorded at two minute intervals until the regions were within 0.1 F of their equilibrium temperature. The total temperature rise was of the order of 20 F starting from a room air temperature of approximately 71 F.

The results are presented in Table 3A.

<u>Test #4 Measurement of Thermal Isolation</u>

The purpose of this test was to determine the degree to which the temperatures of certain regions of the manikin are affected by changes in the temperatures of adjacent regions. Tests were made with the manikin operating in the "automatic mode". The manikin was allowed to reach thermal equilibrium, then the power being delivered to a region was reduced until the temperature was lowered by approximately 10 F. The temperatures of each region under study and the adjacent regions were measured.

The results are presented in Table 4A. It can be seen that a 10 F change in the temperature of a region will result in less than a 1 F change in the adjacent regions. In most cases, the change in temperature of the adjacent regions is less than 0.5 F.

TABLE 3A

TRANSIENT RESPONSE OF MANIKIN

Region	Temperature (F) Initial	Final	Time hrs	min
Head	70.2	89.1	1	08
Chest	71.2	93.4	2	10
Abdomen	71.8	92.0	3	12
Back	71.6	93.6	2	08
Buttocks	72.3	92.6	3	00
Thighs	70.9	87.6	2	30
Calf	70.8	90.7	2	10
Foot	70.8	90.4	2	00
Arm	70.8	92.2	1	30
Forearm	70.2	88.7	1	10
Hand	70.0	93.6	0	38

TABLE 4A

THERMAL ISOLATION TESTS

Region Studied		Adjacent Regions	
Zone	ΔT (F)	Zone	ΔT (F)
Head	9.6	Chest	0
		Back	0
R. Forearm	8.6	R. Hand	0.6
		R. Arm	0.2
L. Calf	10.0	L. Thigh	0.0
		L. Foot	0.4
R. Foot	10.8	R. Calf	0.4
Chest	9.6	Abdomen	-0.1
		Back	0.4
		Head	0.1
		L. Arm	0.1
		R. Arm	0.3

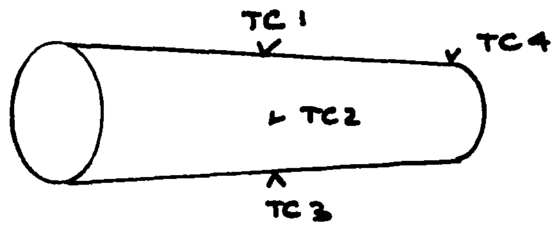
Test #5 Temperature Gradient Measurements

In order to determine the temperature gradients within the various regions of the manikin, a calibrated, copper-constantan (#36 premium grade) differential thermocouple was attached to various areas with aluminum epoxy and the differential temperatures measured by use of a Leeds and Northrup K-3 potentiometer which can resolve a voltage of less than 1 microvolt (0.05 F). The leads were bonded to the manikin with mashing tape to reduce heat losses along the wire. The temperature gradient measurements were made with the manikin operating in an automatic power control mode. The total power dissipation in the manikin was approximately 100 watts (341 Btu/hr). The over-all accuracy of the gradient measurements was judged to be approximately $\pm$ 0.1 F.

The temperature gradient data for each region are presented in the following tables. In all cases, the temperature differences are referred to one leg of the differential thermocouple which was located in the same area as the platinum resistance thermometer used to measure the absolute temperature of each region.

Table 5A

Forearm



TC 1 LOCATED OVER P.R.T

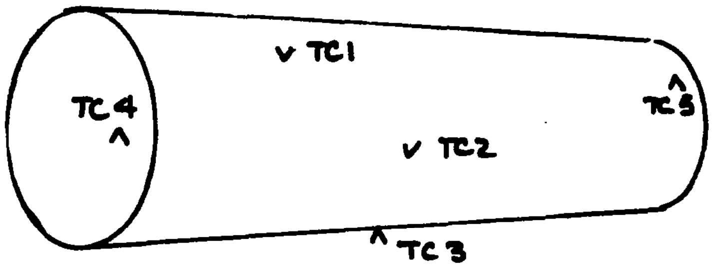
TC 2 - TC1 = 0.26 F

TC 3 - TC1 = 0.11 F

TC 4 - TC1 = 0.11 F

Table 6A

Arm



TC2 - TC1 = 0.15F

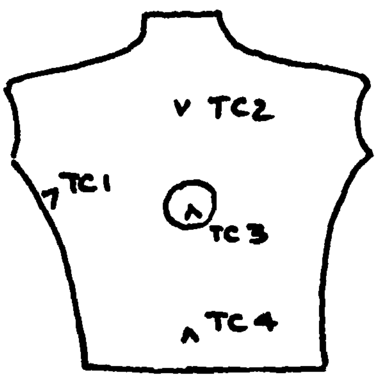
TC3 - TC1 = 0.31F

TC4 - TC1 = 0.07F

TC5 - TC1 = 0.33F

Table 7A

Chest



TC2 - TC1 = 0.4F

TC3 - TC1 = -0.47 F

TC4 - TC1 = 0.04F

Table 8A

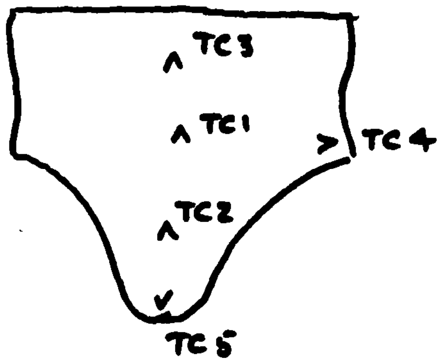
Head

TC 2 - TC 1 = 0.52 F

TC 3 - TC 1 = 0.20 F

Table 9A

Abdomen



TC 2 - TC 1 = 0.12 F

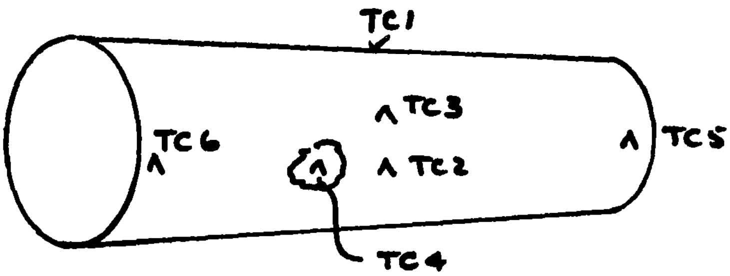
TC 3 - TC 1 = -0.4 F

TC 4 - TC 1 = 0.55 F

TC 5 - TC 1 = -0.20 F

Table 10A

Thigh



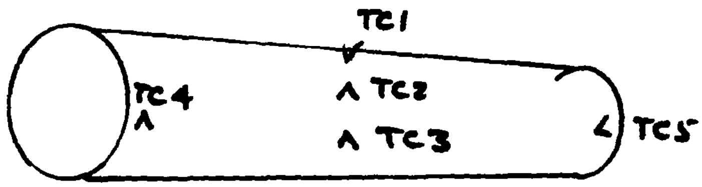
TC2 - TC1 = 0.56F

TC3 - TC1 = 0.13F

TC5 - TC6 = 0.28 F

Table 11A

Calf



TC2 - TC1 = 0.11 F

TC3 - TC1 = 0.15 F

TC5 - TC4 = -0.06 F

Table 12A

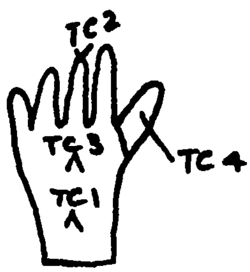
Foot

TC2 - TC1 = -.33F

TC3 - TC1 = - 0.15F

Table 13A

Hand



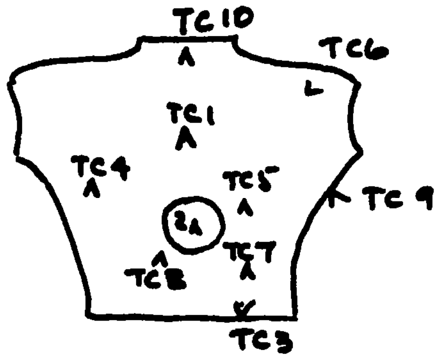
TC2-TC1 = -.95F

TC4-TC1 = - 1.5F

TC3-TC1 = -0.3 F

Table 14A

Back



TC2-TC1 = -1.1F

TC3 - TC1 = -0.7F

TC8 - TC1 = -0.6F

TC7 - TC1 = -0.7F

TC4 - TC1 = 0.5F

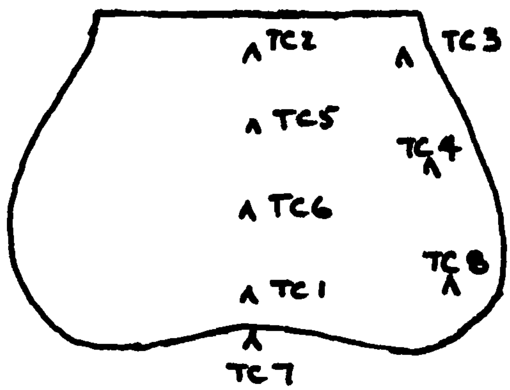
TC5 - TC1 = 0.3F

TC9 - TC1 = 0.43F

TC10 - TC1 = 0.03F

Table 15A

Buttocks



TC2 - TC1 = 0.37 F

TC3 - TC1 = 0.24 F

TC4 - TC1 = 0.04 F

TC8 - TC1 = 0.11 F

NASA-Langley, 1966 CR-644